Report No. M-9

MISSIONS TO THE COMETS

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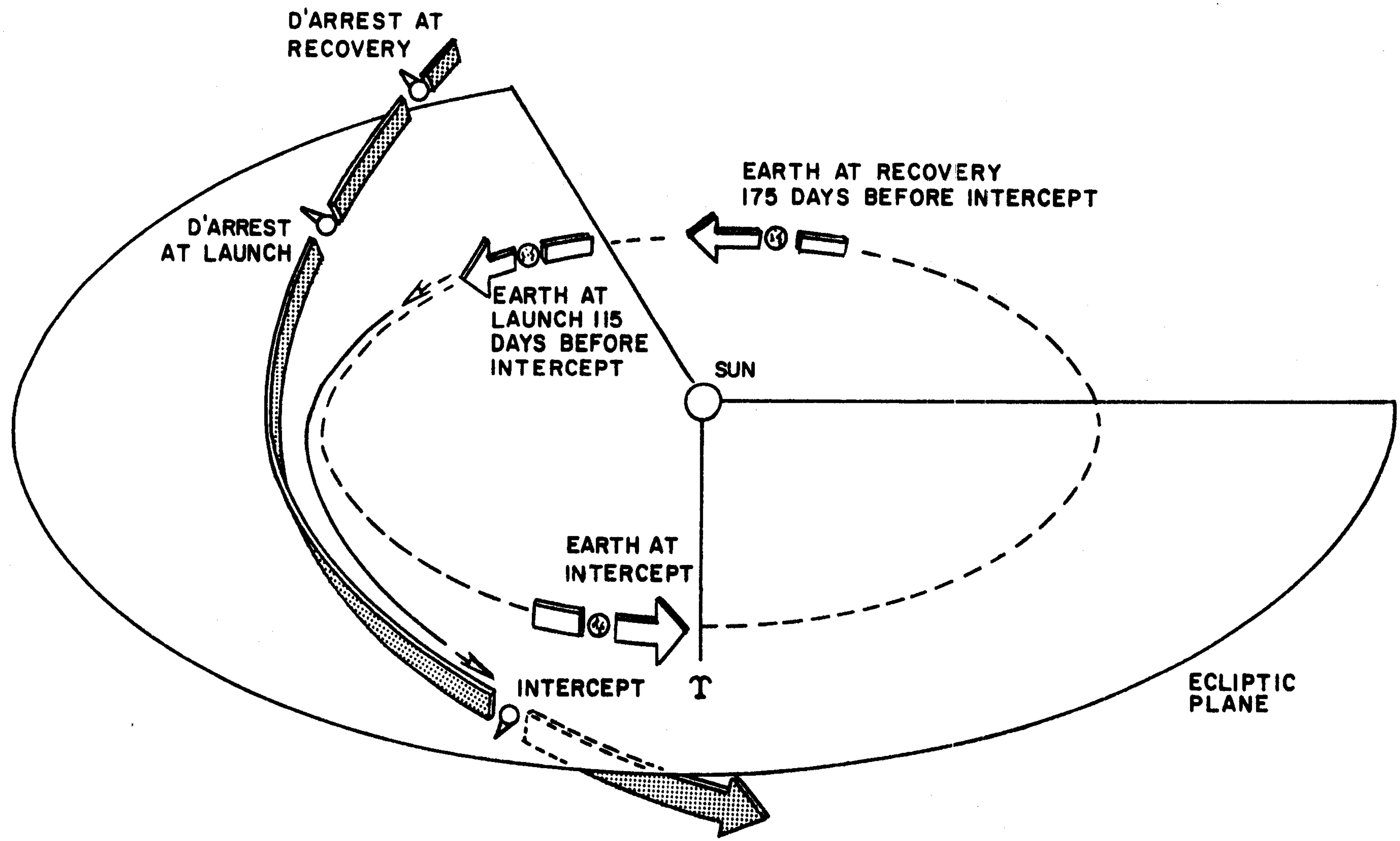

COMET D'ARREST MISSION IN 1976
FRONTISPIECE

SUMMARY

This report is a digest of six Astro Sciences Center/ IIT Research Institute reports covering the general area of preliminary selection and assessment of missions to comets in the years 1965-1986. These reports consider the feasibility of unmanned scientific missions to well-known short-period comets and to new comets. These reports lead to the following conclusions. Opportunities for missions to short-period comets occur at an average rate of one per year; about one in four of these is particularly attractive. If a comet detection network and a quick-response launch facility are availal le in the future, nearly one new comet mission per year would be feasible. In most cases a launch vehicle of the Atlas-Centaur class would be adequate. For almost all missions the fundamental experiments would be measurements of charged particles, dust, and magnetic field in the comet coma and tail, together with measurements aimed at determining the properties of the comet nucleus. For more detailed treatment of comet missions the reader is referred to our Reports No. M-7, P-3, P-9, T-7, T-11 and T-13, listed in the bibliography (Section 6).

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MISSIONS TO THE COMETS

1. INTRODUCTION

The first recorded apparition of a comet occurred in 466 B.C., when Halley's comet was seen. Not until 1577, however, were comets definitely established as solar system objects, and not until 1705 were the first comet orbits determined. Although a great deal of information about comets has been obtained since then, fundamental facts about the origin and the structure of comets continue to elude astronomers.

There are two classes of comets: short-period comets, with periods of less than 1,000 years, and long-period comets (including parabolic and hyperbolic comets), with periods of more than 1,000 years. Since most new comets are long-period, we shall consider only this type of new comet in this report. New short-period comets are similar to well-known short-period comets; since missions to well-known comets are much simpler than missions to new comets, there is no point in considering missions to new short-period comets.

Comets consist of three components: the nucleus, the coma, and the tail. The typical comet nucleus is 1 to 10 km in diameter and is thought to be composed of an icy conglomerate of dust, water, and various hydrocarbons. The coma surrounding the nucleus is 2,000 to 2,000,000 km in size. Trailing away from the coma is the tail, from 10 to 150 million km long.

Comets exhibit a greater range of brightness than any other celestial objects except nova and supernova. Comets range in brightness from visible to the naked eye in daylight to barely visible at night with a large telescope. The majority of short-period comets, however, can be detected only with a large telescope.

The orbits of short-period comets have median parameters: inclination 15 degrees, eccentricity 0.56, perihelion distance 1.3 AU, aphelion distance 5.5 AU, and orbital period 7 years. In general, short-period comets are faint, inactive, and in no sense as spectacular as new comets. Because of their relatively frequent passes, their orbits can be determined and their future returns can be predicted fairly accurately. Thus they form the group of comets most suitable for intercept missions in terms of spaceflight requirements. An average of one potential short-period comet mission occurs each year.

New comets are discovered at an average rate of three to four a year. Because of their size, brightness, and generally high level of activity, they have contributed most to the present cometary knowledge. Thus missions to new comets are also desirable. The most critical parameter in determining new comet mission opportunities is the magnitude at which the comets can be discovered. If all the new comets could be discovered at magnitude 15, which would require an organized search program, and if a launch were possible with only a few months lead time, then almost one mission per year would be possible.

Thus, short-period comets are the most attractive for future missions. Their returns can be predicted, and detailed planning can be carried out. However, short-period comets, with the exception of Halley's tend to be relatively inactive and unspectacular. The brightness and the activity of new comets lend considerable merit to complementing short-period comet missions with new comet missions. However, new comet missions are quite difficult because there is no way of predicting when a new comet will appear.

The comet missions that appear to be feasible over the next twenty years would enable comets to be intercepted near perihelion, where they are most active and bright and can be observed from the Earth. Space probe measurements will serve to supplement the present knowledge of comets and to add new information, which cannot be obtained from Earth, on the characteristics of the nucleus and on the distribution of charged particles, dust, and magnetic fields throughout the coma. Increased knowledge should make it possible to view comets as interplanetary probes, which, by their appearance, indicate the state of the local interplanetary medium and perhaps indicate solar activity. For the comet Kopff in 1983 it is possible to consider both a rendezvous mission and an intercept mission.

The scientific objectives that are the basis for the comet intercept missions are summarized in Table 1. Of course, comet intercepts alone cannot provide all the answers to questions about comets. Ground-based observations, laboratory studies, and artificial comets launched from the Earth are also desirable.

2. SELECTION CRITERIA FOR COMET MISSIONS

The specific comet missions selected must satisfy both the specific objectives and the technological constraints. Fortunately, relatively bright comets are almost always positioned favorably for intercept missions; this greatly simplifies the selection process.

2.1 Short-Period Comet Missions

Because planetary perturbations, particularly by Jupiter, can strongly affect comet orbits, detailed perturbation calculations were performed for each short-period comet before the selection process was started.

Table 2 shows the basic selection criteria* for short-period comet missions.

The first criterion, two recent observed apparitions, provides some assurance that the comet will return in its future apparitions as predicted.

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* Criterion 2, magnitude 12 or brighter at intercept, was not imposed in our very early comet studies.

Table 1

SUMMARY OF SCIENTIFIC OBJECTIVES

Nucleus

- Macroscopic construction (sand bank or ice nucleus model)
- Diameter, shape, mass, density determination
- Constitution (nucleus compounds)
- Temperature and albedo determination
- Method of gas and dust release
- Magnetic field detection
- Possible biological species or organic compounds

Coma

- Mechanism of halo formation
- Determination of parent, daughter, and grand-daughter molecules and ions
- Verification of ionizing and excitation mechanisms
- Nature of reflecting particles
- Relationship between size and brightness as a function of solar distance
- Magnetic field detection

Tail

- Verification of constitution of Type I and Type II or III tails
- Mechanisms causing tail structures
- Establishment of mechanisms for accelerations of tail material
- Magnetic field detection

Table 2

SELECTION CRITERIA FOR PERIODIC COMET MISSIONS

1. Two recent passes observed.
2. Brighter than magnitude 12 at intercept.
3. Recovery 2 months before launch of spacecraft.
4. Recovery magnitude brighter than 20, with 2 hours of visibility in a dark sky.
5. Ideal velocity (ΔV) requirements less than 55,000 ft/sec.

The second criterion, magnitude 12 or brighter at intercept, assures that adequate spectroscopic measurements can be made from Earth at the time of intercept. By correlating such ground-based measurements with spacecraft measurements, a maximum amount of scientific information can be obtained from the mission.

The third criterion, recovery of the comet before launch, accomplishes two things. First, it assures that the comet is going to appear on this apparition. Second, it allows sufficient time for tracking the comet to verify its position in orbit.

Whether two months is too much or too little time for tracking before launch depends somewhat on the individual comet and on the velocity correction that is possible after launch of the spacecraft. If two or three velocity corrections can be applied to the spacecraft after launch, less than two months tracking would probably be needed to attain a 10,000-km miss distance. Even two months of ground-based tracking is probably not adequate for a very precise intercept. In particular, if the mission is designed to intercept within 1,000 km of the nucleus, there would almost certainly have to be a comet acquisition system on the spacecraft as well as capability for trajectory corrections during the last day of the flight.

The fourth criterion, magnitude brighter than 20 and two hour visibility in a dark sky, corresponds to typical comet recovery using a large telescope such as the 40-inch reflector at the U. S. Naval Observatory in Flagstaff, Arizona.

The fifth requirement, ideal velocity (ΔV) of less than 55,000 ft/sec (the upper limit of the S-1B Centaur capability), is redundant in most cases. The ideal velocity requirements for missions to almost every comet that was brighter than magnitude 12 at intercept were significantly less than 55,000 ft/sec.

Table 3 illustrates the selection process.

Table 3

SELECTION STATISTICS FOR SHORT-PERIOD COMET MISSIONS

Comets considered		37
Perihelion dates		2/65 to 1/86
Number of apparitions		110
Comets eliminated on brightness-energy considerations		88
Number of possible missions:		22
Primary	5	
Secondary	12	
Marginal	5	

Initially 37 comets were selected that had two recent observed apparitions and perihelia between February 1965 and January 1986. The 37 comets will have 110 apparitions in the 1965-1986 time span. Of the 110 apparitions, 88 were eliminated on the basis of magnitude 12 and ΔV less than 55,000 ft/sec. Of the 22 missions remaining, 5 were selected as being of primary interest, 12 as being of secondary interest, and 5 being as of marginal interest. Most of the marginal missions are magnitude 13 at intercept; they were included to make sure that no reasonable missions are omitted. The final breakdown into 5 of primary interest and 12 of secondary interest is somewhat subjective, particularly since comet brightness is poorly known and not easily predictable.

We believe that all 22 missions are of interest in the next 20 years and that each of the 5 missions of primary interest should be seriously considered. Tables 4, 5, and 6 detail the 22 missions.

2.2 New Comet Missions

It is impossible to select new comet missions more than a few months in advance, since there is no way of predicting new comet apparitions. Because of the possible merit of using new comet missions to complement short-period comet missions, the feasibility of new comet missions was assessed by analyzing which of the new comets discovered between 1945 and 1960 would have satisfied the criteria imposed for short-period comet missions. These criteria are: ΔV less than 55,000 ft/sec, brightness greater than magnitude 12 at intercept, and two months of tracking before launch.

Table 7 summarizes the selection statistics for the new comet missions.

Table 4

CHRONOLOGICAL SUMMARY TABLE OF MISSIONS OF PRIMARY INTEREST

Comet Name; Perihelion Date	Trajectory Data: Launch	Trajectory Data: Intercept	Sighting Data: Launch	Sighting Data: Intercept	Comments
Tempel 2 8/13/67	Date = 3/30/67 V = 43,000 ft/sec TF = 110-135 days	1 day before perihelion VHP = 11-12 km/sec RC = 0.42 AU	Mag 18 Visible 4 hr at +25° 3 hr at -25°	Mag 10.5 Visible 7 hr at +25° 10 hr at -25°	A bright comet; early recovery, easy trajectories, excellent sighting; some spectroscopic data; probably the best mission in 1965-1975.
Encke 4/28/74	Date = 9/13/73 V = 44,400 ft/sec TF = 240-270 days or	30 days after perihelion VHP = 28 km/sec RC = 0.38 AU	Mag 22 Visible 5 hr at +25° 6 hr at -25°	Mag 9 Visible 1 hr at +25° 4 hr at -25°	A bright comet with short period (3.3 yr) and perihelion distance; very interesting and well known, but difficult to see at perihelion; high VHP makes intercept mission difficult.
	Date = 2/7/74 V = 47,700 ft/sec TF = 80-110 days	43 days after perihelion VHP = 35-38 km/sec RC = 0.40 AU	Mag 18 Visible 5 hr at +25° 3.5 hr at -25°	Mag 8 Not visible at +25° 2 hr at -25°	
D'Arrest 8/14/76	Date = 4/21/76 V = 41,200 ft/sec TF = 85-115 days	At perihelion VHP = 13.0 km/sec RC = 0.18 AU	Mag 20 Visible 4.7 hr at +25° 4.0 hr at -25°	Mag 11 Visible 7.5 hr at +25° 9.8 hr at -25°	A very excellent mission; probably the best between 1965 and 1985 in almost every respect.
Kopff 8/18/83	Date = 2/26/83 V = 43,000 ft/sec TF = 175-190 days	15 days after perihelion VHP = 8.0-9.0 km/sec RC = 1.0 AU	Mag 17 Visible 3.5 hr at +25° 2.4 hr at -25°	Mag 12 Visible 4.6 hr at +25° 6.6 hr at -25°	Very good recovery is an asset; greater brightness is desirable. A possible rendezvous mission.
H lley 1/8/86	Date = 1/85 V = 43,000 ft/sec TF = 300 days or	50 days before perihelion VHP = 65 km/sec RC = 0.5 AU	Mag 19 Visible 8 hr at +25° 6 hr at -25°	Mag 4 Visible 6 hr at +25° 4 hr at -25°	The bright, outstanding comet; however, the extremely high VHP imposes problems for a mission.
	Date = 7/85 V = 42,500 ft/sec TF = 210 days	50 days after perihelion VHP = 69 km/sec RC = 1.25 AU	Mag 16 Poor visibility	Mag 5 Visible 2 hr at +25° 3 hr at -25°	

Table 5

CHRONOLOGICAL SUMMARY TABLE OF MISSIONS OF SECONDARY INTEREST

Comet Name; Perihelion Date	Trajectory Data: Launch	Trajectory Data: Intercept	Sighting Data: Launch	Sighting Data: Intercept	Comments
Perrine-Mrkos 10/31/68	Date = 4/4/68 ΔV = 45,400 ft/sec TF = 195-225 days	15 days after perihelion VHP = 12-14 km/sec RC = 0.33 AU	Mag 19 Visible 0.3 hr at +25° 0.2 hr at -25°	Mag 8 Visible 10 hr at +25° 7 hr at -25°	Not a well known comet; particularly bright at intercept; few weeks delay in recovery would not change the trajectory significantly.
Encke 1/9/71	Date = 6/30/70 ΔV = 45,900 ft/sec TF = 110-140 days	53 days before perihelion VHP = 29-30 km/sec RC = 0.43 AU	Mag 22 Visible 0.3 hr at +25° 0.7 hr at -25°	Mag 11 Visible 6.5 hr at +25° 4 hr at -25°	Very marginal recovery; Encke is well enough known for recovery 30 days before launch.
Giacobini-Zinner 8/3/72	Date = 3/15/72 ΔV = 53,000 ft/sec TF = 150 days	9 days after perihelion VHP = 20 km/sec RC = 1 AU	Mag 20 Visible 1.5 hr at +25° 0.5 hr at -25°	Mag 12 Visible 3 hr at +25° 2.5 hr at -25°	An interesting, bright comet, but with very marginal recovery; 30 days less between recovery and launch reduces ΔV to 48,000 ft/sec.
Schwassmann-Wachmann 1 1/30/74	Date = 2/3/71 ΔV = 51,900 ft/sec TF = 920-950 days	142 days before perihelion VHP = 6-7 km/sec RC = 4.5-5 AU	Observable every year; Mag 18 at opposition; subject to fluctuations	Observable every year; Mag 18 at opposition; subject to fluctuations	Perihelion of 5.4 AU makes this always difficult shot. Fluctuations in comet brightness are of interest.
Honda-Mrkos-Pajdusakova 12/31/74	Date = 10/26/74 ΔV = 46,900 ft/sec TF = 75-100 days	34 days after perihelion VHP = 24-27 km/sec RC = 0.23 AU	Mag 20 Visible 5.5 hr at +25° 6.5 hr at -25°	Mag 9 Not visible at +25° Visible 5 hr at -25°	A relatively bright apparition; not a well known comet.
Grigg-Skjellerup 4/9/77	Date = 1/2/77 ΔV = 46,100 ft/sec TF = 70-100 days	0 days VHP = 15.0 km/sec RC = 0.22 AU	Mag 20 Visible 5 hr at +25° 4.3 hr at -25°	Mag 11 Visible 3 hr at +25° 5.2 hr at -25°	A good mission although greater brightness is desirable.
Encke 12/6/80	Date = 8/19/80 ΔV = 53,000 ft/sec TF = 60-80 days	30 days before perihelion VHP = 21-23 km/sec RC = 4-8 AU	Mag 20 Visible 2.5 hr at +25° 3.1 hr at -25°	Mag 7 Visible 2.9 hr at +25° 0 hr at -25°	High energy, high closing velocity and marginal recovery, but a bright apparition.
Tuttle 12/13/80	Date = 5/21/80 ΔV = 45,800 ft/sec TF = 160-190 days	20 days before perihelion VHP = 34 km/sec RC = 0.54 AU	Mag 20 Visible 0 hr at +25° 2 hr at -25°	Mag 9 Visible 2.2 hr at +25° 4.9 hr at -25°	The high VHP is a problem.

Table 5 (Cont'd)

Comet Name; Perihelion Date	Trajectory Data		Sighting Data		Comments
	Launch	Intercept	Launch	Intercept	
Grigg-Skjellerup 5/13/82	Date = 1/17/82 ΔV = 45,500 ft/sec TF = 105-130 days	0 days VHP = 18.0 km/sec RC = 0.33 AU	Mag 20 Visible 6.7 hr at +25° 5.6 hr at -25°	Mag 11 Visible 7.3 hr at +25° 6.3 hr at -25°	A good mission, although greater brightness is desirable.
D'Arrest 10/13/82	Date = 2/17/82 ΔV = 44,000 ft/sec TF = 210-240 days	5 days after perihelion VHP = 12.0-15.0 km/sec RC = 1.25 AU	Mag 20 Visible 3 hr at +25° 1.2 hr at -25°	Mag 12 Visible 3.1 hr at +25° 4 hr at -25°	This apparition could provide data subsequent to the 1976 mission.
Encke 3/27/84	Date = 10/22/83 ΔV = 52,000 ft/sec TF = 185-200 days	38 days after perihelion VHP = 27 km/sec RC = 0.85 AU	Mag 20 Visible 7.9 hr at +25° 7.7 hr at -25°	Mag 11 Visible 1.2 hr at +25° 3.5 hr at -25°	This apparition is not quite as good as the 1980 apparition.
Giacobini-Zinner 9/4/85	Date = 4/24/85 ΔV = 48,500 ft/sec TF = 155-170 days	8 days after perihelion VHP = 21 km/sec RC = 0.50 AU	Mag 20 Visible 3.3 hr at +25° 2.6 hr at -25°	Mag 12 Visible 5.2 hr at +25° 5.9 hr at -25°	A reasonably good opportunity.

Table 6

CHRONOLOGICAL SUMMARY TABLE OF MISSIONS OF MARGINAL INTEREST

Comet Name; Perihelion Date	Trajectory Data		Sighting Data		Comments
	Launch	Intercept	Launch	Intercept	
Honda-Mrkos-Pajdusakova 9/25/69	Date = 7/15/69 ΔV = 60,000 ft/sec TF = 50-60 days	10 days after perihelion VHP = 12-15 km/sec RC = 0.5-1.0 AU	Mag 20 Visible 4.0 hr at +25° 5.9 hr at -25°	Mag 10 Visible 1.3 hr at +25° 0.20 hr at -25°	Launch 2 weeks after recovery reduces ΔV to 43,500 ft/sec; mag 10 at intercept is favorable.
Pons-Winnecke 7/18/70	Date = 3/1/70 ΔV = 45,600 ft/sec TF = 135-155 days	16 days after perihelion VHP = 15 km/sec RC = 0.7 AU	Mag 20 Visible 7.4 hr at +25° 3.0 hr at -25°	Mag 13 Visible 3.3 hr at +25° 5.9 hr at -25°	Launch at recovery has $\Delta V \sim$ 40,500 ft/sec; the mission is reasonably favorable except somewhat faint at intercept.
Kopff 10/6/70	Date = 12/31/70 ΔV = 44,000 ft/sec TF = 280-300 days	21 days after perihelion VHP = 9.8 km/sec RC = 1.90 AU	Mag 19 Visible 1.7 hr at +25° 0.50 hr at -25°	Mag 13 Visible 1.9 hr at +25° 2.6 hr at -25°	Somewhat faint at intercept and otherwise not particularly favorable.
Tuttle-Giacobini-Kresak 6/7/73	Date = 12/5/72 ΔV = 51,000 ft/sec TF = 190 days	5 days after perihelion VHP = 14-15 km/sec RC = 1.0 AU	Mag 20 Visible 4.8 hr at +25° 4.0 hr at -25°	Mag 13 Visible 3.5 hr at +25°	Somewhat faint at intercept. Launch at recovery reduces ΔV to 44,000 ft/sec.
Borrelly 2/18/81	Date = 6/30/80 ΔV = 48,200 ft/sec TF = 220-245 days	12 days after perihelion VHP = 18-20 km/sec RC = 1.52 AU	Mag 20 Visible 0.9 hr at +25° 4.5 hr at -25°	Mag 13 Visible 2.9 hr at +25° 1.5 hr at -25°	Somewhat faint at intercept. Launch at recovery reduces ΔV to 41,000 ft/sec.

Table 7

SELECTION STATISTICS FOR NEW COMET MISSIONS

New comets discovered from 1945 to 1960	71
New comets of periods less than 1000 years	17
Long-period new comets	54 = 3.5/year
Missions possible after actual discovery	2 = 1/7.5 years
Missions possible if all comets were discovered at magnitude 15, by a comet search program	10 = 1/1.5 years

Seventy-one new comets were discovered between 1945 and 1960. Of the 71, 17 have periods of less than 1,000 years. These 17 comets have physical properties similar to those of the well known short-period comets and were eliminated from further consideration, since a mission to a well known comet is far easier than one to a new comet.

Thus there were 54 new, long-period comets in 15 years, or an average of 3.5 per year. Because most new comets are discovered near perihelion, only two missions would have been possible to these 54 after the comets were discovered. Therefore, within the framework of current discovery techniques, there would be only one new comet mission every 7.5 years.

Our conclusion is that new comet missions could be feasible if a comet search program were implemented to discover the new comets earlier, so that the launch energy requirements could be greatly reduced. For example, if all the new comets had been discovered at magnitude 15, perhaps by using the Baker-Nunn camera system, there would have been one opportunity per 1.5 years.

There are now 12 Baker-Nunn cameras in a worldwide system set up by the Smithsonian Astrophysical Observatory under a NASA contract to track artificial satellites. Because of their wide field of view and fast response time, the Baker-Nunn system of 12 cameras can search the entire night sky in 1 hour.

The major problem would be distinguishing the magnitude-15 comet from the many other magnitude-15 objects in the sky. There would be difficulty particularly in distinguishing between comets and asteroids, since almost all comets are nearly stellar in appearance at magnitude 15. Nevertheless, we believe that with some effort a system similar to the Baker-Nunn cameras could be used to discover new comets.

Table 8 compares the average parameters for short-period and new, long-period comet missions. The only significant differences between the two types are that new comet missions have higher approach velocities and new comets are brighter at intercept.

Table 8

AVERAGE PARAMETERS FOR COMET MISSIONS

	Short-Period Comets	New Comets
Number in sample	17	10
Ideal velocity (ΔV)	46,600 ± 3,800	45,500 ± 3,700 ft/sec
Flight time (TF)	205 ± 198	186 ± 92 days
Velocity of approach (VHP)	22 ± 13	50 ± 17 km/sec
Communications distance (RC)	1.1 ± 1.7	1.2 ± 1.2 AU
Magnitude at intercept	10.5 ± 2.9	8.5 ± 3.3

3. PAYLOADS FOR COMET MISSIONS

When determining the experiments to be included in a mission, comets must be considered individually. The experiments conform to a general, broad outline but should be tailored to the brightness and the activity of the particular comet whenever possible.

The types of instrumentation suggested for comet intercept missions include plasma probes, magnetometers, spectrophotometers, mass spectrometers, dust-particle detectors, and television cameras. Television is included to observe the surface and the macroscopic construction of the nucleus. Some of the instruments would operate throughout the flight to gain information on the interplanetary medium. The data would be used to compare the field and particle distribution in space with the magnetic field and particle distribution in the coma and, in particular, to detect any transition region between the two.

Table 9 indicates the type of experimental payload that could provide useful information by flying through a cometary coma at a miss distance of approximately 10,000 km from the nucleus. Because of the high approach velocity, and the 10,000-km miss, no instrumentation is included for observing the nucleus. This experimental payload should provide an indication of the constitution of the coma and should also provide data on magnetic field, charged and dust particle distributions, and plasma temperature.

Table 9

POSSIBLE EXPERIMENTAL PAYLOAD
FOR FLYBY MISSIONS
10,000-km miss distance

Instrument	Remarks
Plasma probe (Faraday cup)	20 energy levels per minute
Magnetometer: fluxgate	One 3-axis measurement each 3 sec to match plasma data
rubidium	3-axis absolute measurements
Mass spectrometer	45 mass channels per minute, 1000-km resolution
Dust-particle detector	Sensitivity 3×10^{-7} dyne-sec (10^{-13} grams at 30 km/sec)
Experimental weight	25 lb
Experimental power	20 watts
Experimental data rate	20 bits/sec

Table 10 shows a possible extension of the basic pay load for a mission in which the miss distance is only 1,000 km from the nucleus but in which the approach velocity is still high. Three additions are made. (1) A spectrophotometer is included to view the comet as a whole at approach, to view the coma with relatively high spatial resolution from close range, and to observe the spectrum of the nucleus itself. The spectrometric measurements would be correlated with Earth-based measurements. (2) Fast-response plasma probes and (3) magnetometers are included to determine the fine structure of the plasma inside and outside the coma. A response time of msec, which will give a spatial resolution of about 20 meters at an approach velocity of 20 km/sec, is suggested. For all the plasma and magnetic field measurements it is important that the data be correlated in terms of time and of the position of the spacecraft in the coma. Television will be used to observe the nucleus in at least two colors. The high velocity, however, restricts the system to only about four pictures before the camera is out of range.

Table 10

POSSIBLE EXPERIMENTAL PAYLOAD
FOR CLOSE FLYBY MISSIONS
1,000-km miss distance

Instrument	Remarks
Particles and fields	As for 10,000-km flyby
Fast-response plasma probe	Measurement each millisecond to determine fine structure
Fast-response magnetometer	3-axis measurement each millisecond to match plasma data
Spectrophotometer	1 coarse spectrum each 5 min during approach and intercept
Television	4 pictures of nucleus
Experimental weight	75 lb
Experimental power	40 watts
Experimental data rate	630 bits/sec

Table 11 shows a modification of this payload for rendezvous missions in which the miss distance is still 1,000 km but the approach velocity is reduced to 100 m/sec. While the experiments are somewhat different, the weight class of the scientific payload is the same as for a close intercept mission. The spacecraft will stay in the vicinity of the nucleus for a number of days and thus will allow much information to be obtained. The television system can obtain pictures of the nucleus at a rate of about one picture every 4 or 5 min. A fast-response plasma probe and a magnetometer are not needed to obtain the fine structure because the spacecraft velocity is relatively low

Table 11

POSSIBLE EXPERIMENTAL PAYLOAD
FOR RENDEZVOUS MISSIONS
100-m/sec flyby velocity

Instrument	Remarks
Particles and fields	As for 10,000-km flyby
Spectrophotometer	1 coarse spectrum each 5 min during approach and intercept
Television	15 pictures of nucleus per hour
Experimental weight	75 lb
Experimental power	35 watts
Experimental data rate	125 bits/sec

The three experimental payloads outlined in Tables 9, 10, and 11 illustrate the differences in the experimental constraints imposed by the intercept parameters. They represent typical examples but by no means exhaust the possibilities of comet intercept experiments.

An environmental constraint is imposed by passing through the coma of a comet. It is anticipated that a considerable flux of dust particles, ions, and molecules will bombard the spacecraft which may represent a hazard to the integrity of the spacecraft system. Some shielding will have to be provided. Solar cells, in particular, are not likely to survive for very long in a cometary environment. Therefore RTG power supplies are suggested, despite the fact that they require shielding and are somewhat heavier than solar cell power supplies.

4. DESCRIPTIONS OF A FEW SELECTED MISSIONS

The missions to the five short-period comets of primary interest are summarized in Table 12.

4.1 Comet Tempel 2, 1967

Comet Tempel 2 has a very favorable apparition in 1967; a comparable mission opportunity does not occur again until 1976, when D'Arrest's comet will be an attractive target. Tempel 2 has made 13 observed appearances since it was discovered in 1873, and in 1967 it will be as close to Earth - 0.4 AU - as it ever is. The comet has a period of 5 years and is inclined 12 degrees to the ecliptic plane. In 1967 its coma diameter should be about 50,000 km and its brightness magnitude 10. Figure 1 shows the trajectory for the Tempel 2 mission in 1967.

4.2 Comet Encke, 1974

The 1974 apparition of Encke is the most suitable Encke mission in the 1965-1986 period. Encke has the shortest period, 3.3 years, of any periodic comet and has been seen on almost 50 apparitions. Because of its short period and 11.9-degree inclination, all Encke missions are characterized by approach velocities of 20 to 40 km/sec. If a comet seeker can be made available before 1974, it should be possible to

Table 12

SUMMARY OF COMET INTERCEPT MISSIONS

	Tempel 2	Encke	D'Arrest	Kopff	Halley
Perihelion date	Aug 1967	Apr 1974	Aug 1976	Aug 1983	Jan 1986
Mission type	Flyby	Flyby	Flyby	Rendezvous	Flyby
Miss distance (km)	10,000	1,000	1,000	1,000	1,000
Flyby velocity (km/sec)	11	35	13	0.1	69
Time in coma (hours)	1	0.6	4	240	1
Communications distance (AU)	0.42	0.4	0.18	1	1.25
Experiment weight (lb)	25	75	75	75	75
Propulsion weight (lb)	0	400	140	8,700	900
Estimated spacecraft weight (lb)	250	900	625	10,000	1,900
Launch vehicle	Atlas-Centaur	Atlas-Centaur + kick stage	Atlas-Agena	Saturn 1B-Centaur	Atlas-Agena or Atlas-Centaur

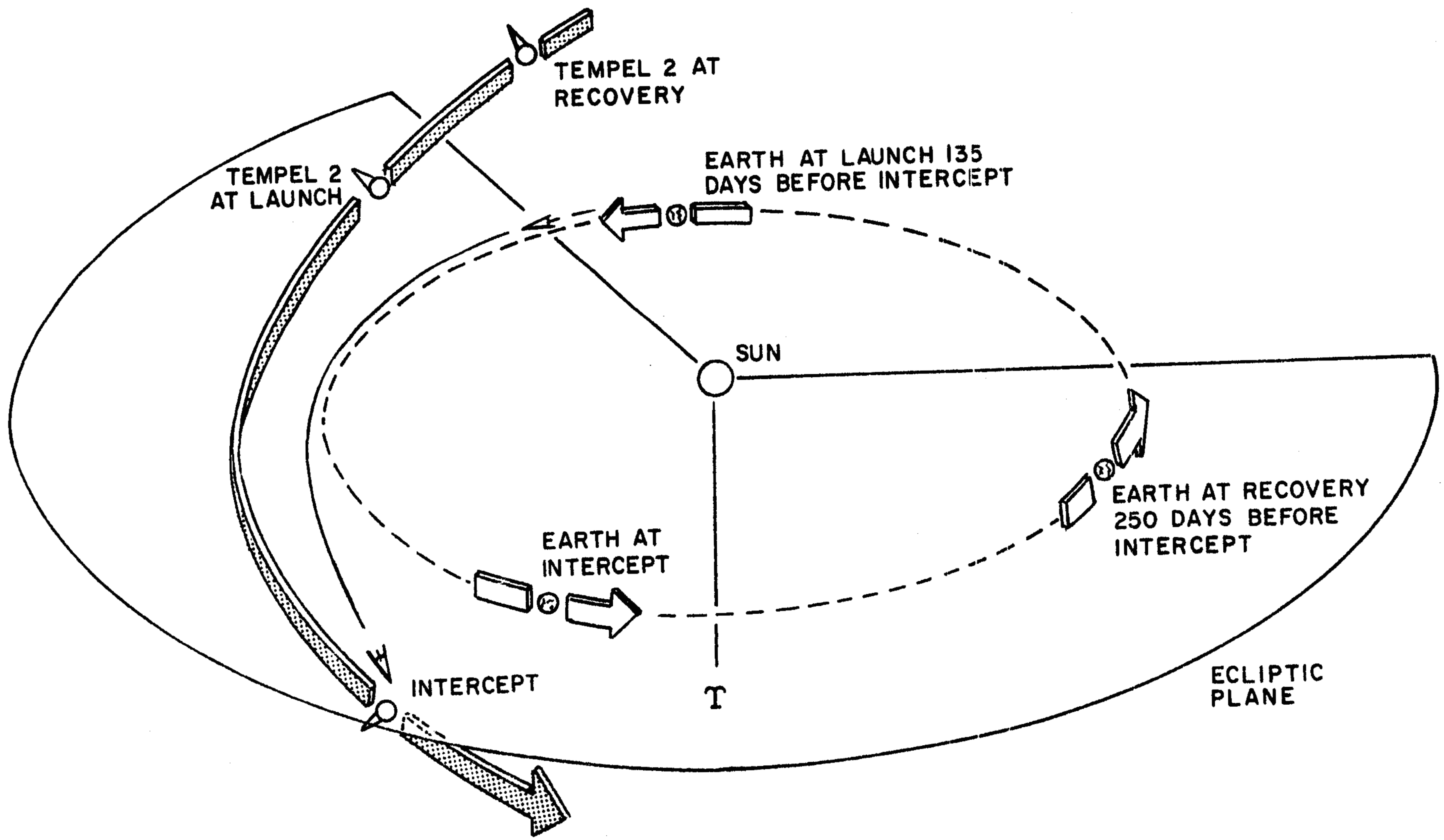

FIGURE 1. 135 DAY TRAJECTORY TO TEMPEL 2 (1967)

consider a flyby mission to within 1,000 km of the nucleus.

The 75 pound experimental payload is proposed as part of the total spacecraft weight of 900 pounds. The major contributors to this total weight are the RTG power supply, weighing 100 pounds, and about 400 pounds of midcourse guidance propulsion. The propulsion provides a velocity increment of about 1 km/sec, which is necessary to achieve the small miss distance since the approach velocity is 35 km/sec.

Figure 2 shows the trajectory for the suggested mission.

4.3 Comet D'Arrest, 1976

A fairly significant perturbation of D'Arrest, by Jupiter, is expected in 1968, and the calculated change in orbital parameters indicates a bright apparition in 1976. D'Arrest's orbit is inclined 17 degrees, its period is 6 years and its perihelion distance 1.18 AU.

A 75 pound experimental payload is suggested, since it would be possible to achieve a miss distance of 1,000 km from the nucleus. The spacecraft weight of 625 pounds includes 140 pounds for a 400 m/sec midcourse correction. The short communications distance of 0.18 AU makes only a small demand on the telemetry system.

Figure 3 shows the orbit and the spacecraft trajectory. The ideal velocity necessary is little more than that required to escape from the Earth.

The 1976 apparition of D'Arrest is probably the most attractive mission before Halley's comet. Although the

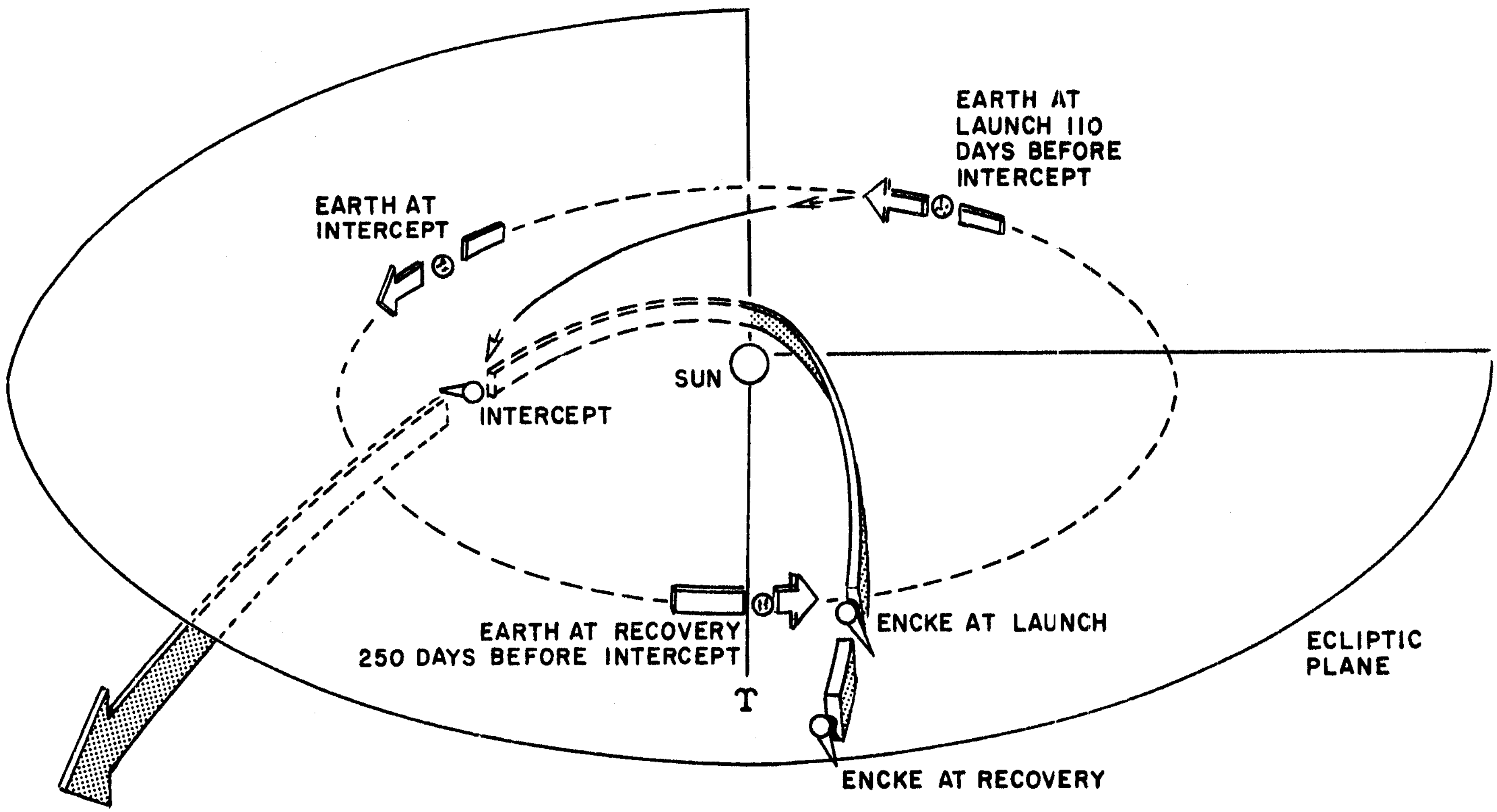

FIGURE 2. 110 DAY TRAJECTORY TO ENCKE (1974)

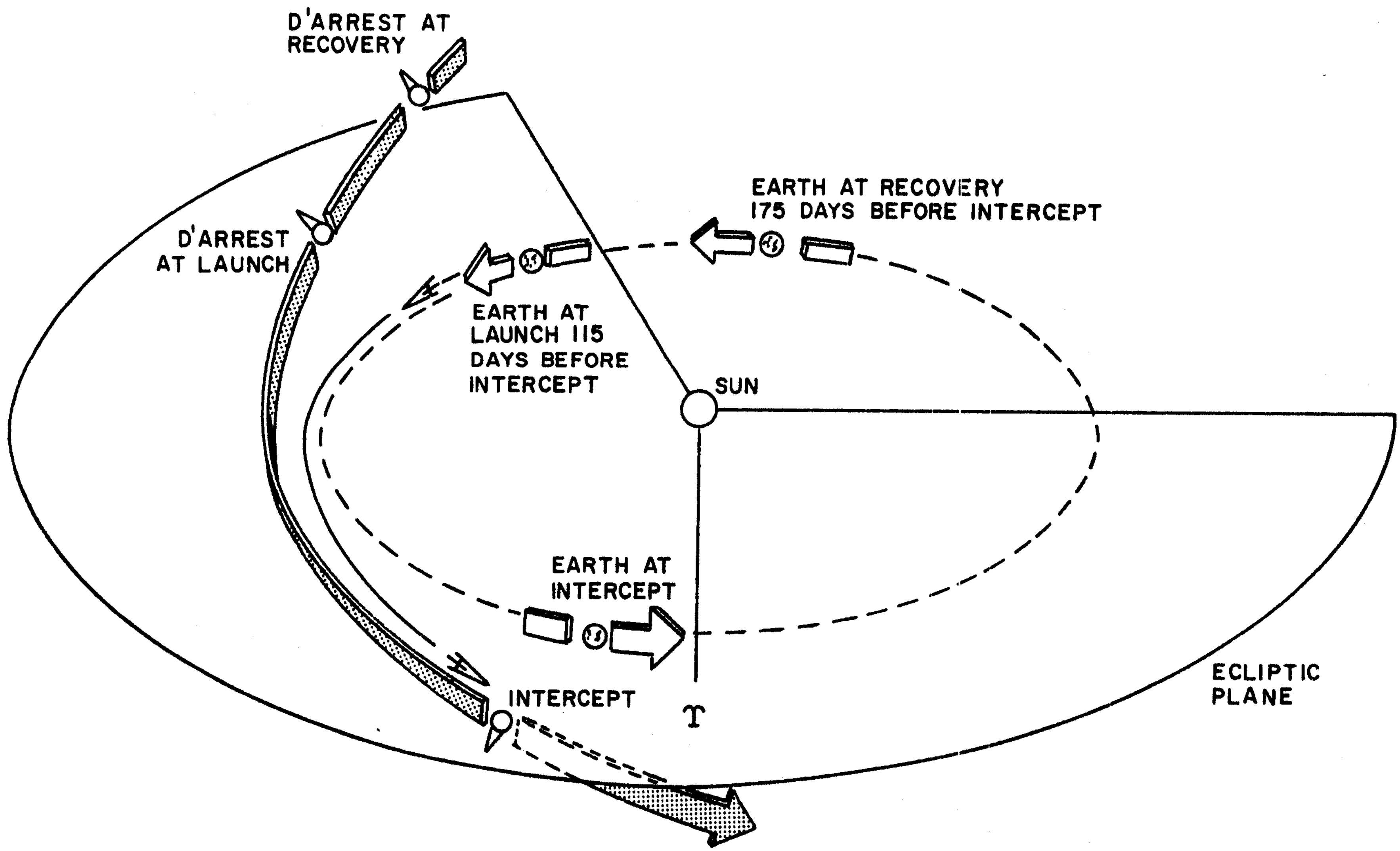

FIGURE 3. 115 DAY TRAJECTORY TO D'ARREST (1976)

comet is not unusually spectacular, all of the factors are very favorable for the 1976 mission. The 1970 apparition would allow verification of the perturbed orbital parameters and the brightness, and the 1982 apparition would provide follow-up scientific data after the 1976 intercept.

4.4 Comet Kopff, 1983

Comet Kopff is included in the list of selected missions because of the relatively low approach velocity, 8 km/sec, which makes it possible to consider a rendezvous mission. Kopff is an unspectacular periodic comet with a period of 6 years and an orbit inclined at 4.7 degrees to the ecliptic plane.

A 75 pound class of experimental payload as suggested (Table 11) is a very small part of the spacecraft weight of about 10,000 pounds. The major part of this total, about 8,300 pounds, is taken up by the terminal retro-rocket and its fuel. Increases in the experimental payload weight would result in large increases in the total weight due to the terminal propulsion. Because this large total weight has to be guided to within 1,000 km of the nucleus, an additional 650 pounds has to be allocated for the 250 m/sec midcourse guidance correction. Furthermore, attitude control of this large mass will require about 200 pounds of control propulsion. This example shows the large weight investment required when the approach velocity is significantly reduced by chemical retro-rockets.

Figure 4 shows the comet orbit and the spacecraft trajectory.

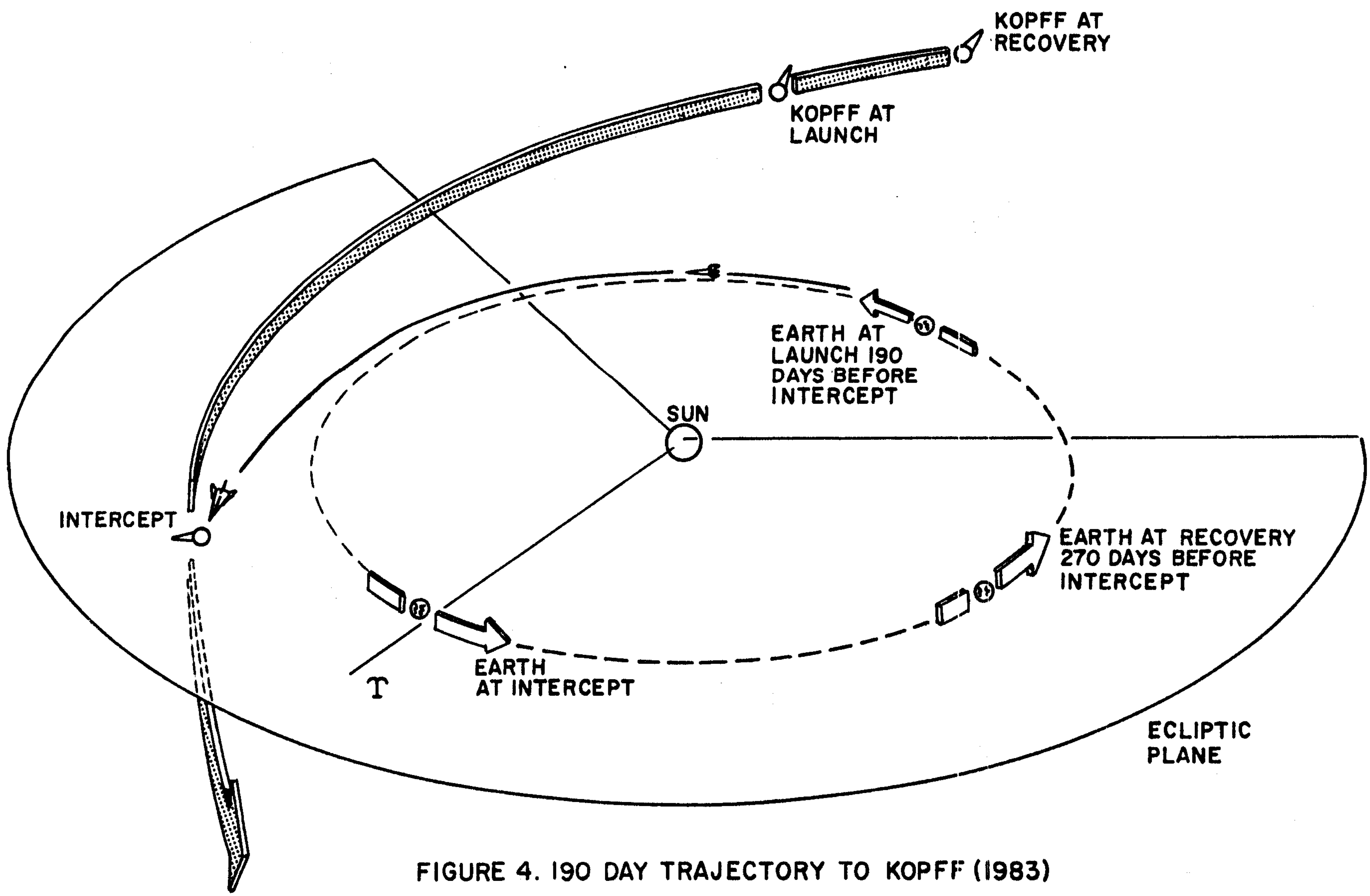

FIGURE 4. 190 DAY TRAJECTORY TO KOPFF (1983)

4.5 Halley's Comet, 1986

Halley's comet is the most outstanding and well known periodic comet. Since its period is 76 years, and since it is such an interesting comet, Halley's should be considered for a mission. Recorded apparitions of Halley's comet extend back to the year 466 B.C. A worldwide study was made at its last appearance, in 1910 and a great deal of information was obtained at that time. This information can be used, together with the results of intercept missions to other comets, to define the experimental payload.

A miss distance of 1,000 km has been suggested, which will be difficult but not impossible to attain. The difficulty is the high approach velocity of 69 km/sec due primarily to Halley's retrograde orbit. A 75 pound experimental payload results in a spacecraft weight of approximately 1,900 pounds. This includes the propulsion (900 pounds) required to provide a velocity increment of 2 km/sec necessary to achieve the desired miss distance.

The 75 pound experimental payload can provide answers to many of the scientific questions concerning Halley but larger payloads may be possible based on more detailed mission studies. For example, it would be desirable to significantly reduce the approach velocity, which would require large launch vehicles and a thrusted stage. Such missions could alter the payload considerations.

Figure 5 shows Halley's orbit and the spacecraft trajectory for an intercept mission. Recovery should be possible some 200 days before launch and before Halley goes into conjunction with the Sun.

5. CONCLUSIONS

Comet intercept missions can play a large role in the understanding of the nature and origin comets, and can contribute to our understanding of the dynamics and origin of the solar system. In particular, they can provide information on the nucleus, the distribution of the charged particles, and the magnetic field in the neighborhood of a comet. This type of data is extremely difficult if not impossible to obtain from Earth.

Our analysis of the possible opportunities for missions to periodic comets indicated that the apparitions of at least 17 periodic comets are suitable for intercept missions in the next 20 years and that 5 are of particular interest. In addition, given a modest sky-searching facility such as can be provided with Baker-Nunn or similar cameras, the potential opportunities for intercept missions to new comets are nearly one per year.

Not only are the number of opportunities for comet missions sufficient but also both the experimental and the total payloads are within the foreseeable state of the art and are compatible with projected launch vehicle capabilities.

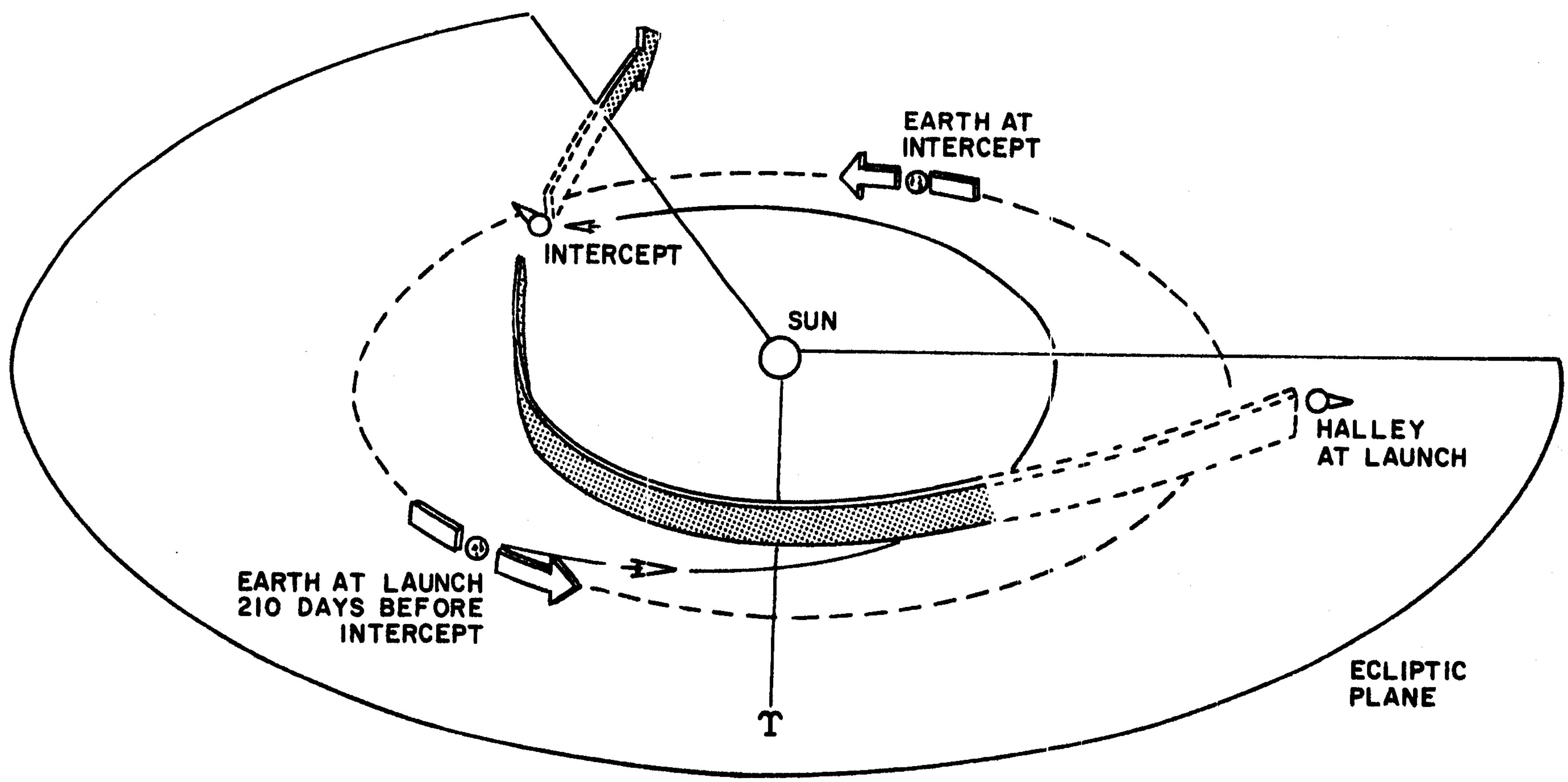

FIGURE 5. 210 DAY TRAJECTORY TO HALLEY (1986)

A reasonable plan for the future is a flyby mission to a short-period comet, perhaps comet D'Arrest in 1976, followed by other missions to periodic comets, especially to Halley's comet, and by missions to new comets.

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7. <u>GLOSSARY</u>

ΔV — Ideal velocity, that is, the total velocity increment that must be given to the spacecraft on leaving Earth:

$$\Delta V = \sqrt{(36{,}178)^2 + (VHL)^2} + 4000$$

Here, 36,178 ft/sec is the characteristic velocity for Earth escape launching from Cape Kennedy and 4000 ft/sec is a correction for gravitational and frictional losses during launch.

VHL — Launch hyperbolic excess speed, the magnitude of the difference between the Earth's velocity vector and the spacecraft's velocity vector at time of injection of the spacecraft into the intercept trajectory

TF — Flight time of spacecraft from launch to intercept.

VHP — Velocity of approach of spacecraft relative to the comet.

RC — Communications distance, or distance between the Earth and the comet at time of spacecraft arrival at the comet.